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A. D. LITTLE, INVESTIGATION OF A TIME DELAY MECHANISM

Report to
FREE EUROPE COMMITTEE, INC.

STAT

April 15, 1958
C-60385

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ARTHUR D. LITTLE, INC.

April 15, 1958

Free Europe Committee, Inc.
2 Park Avenue
New York 16, New York

STAT

Attention: [redacted]

Gentlemen: C-60385

We submit herewith our report on the investigation of a time delay mechanism. We have enjoyed working with you on this problem and would look forward to working with you once again.

Respectfully submitted,

Arthur D. Little, Inc.

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Arthur D. Little, Inc.

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I. SUMMARY

PURPOSE AND SCOPE

This report summarizes the work done by Arthur D. Little, Inc. for the Free Europe Committee, Inc. in a feasibility study and design of a suitable device for the time-delay release of leaflets from balloons.

CONCLUSIONS

1. The most satisfactory device is based on the controlled leakage of gas in a plastic cylinder-and-piston mechanism driven by the balloon's load of leaflets.

The device consists of a 1-inch diameter by 4-inch long cylinder of polyvinyl chloride (PVC). The cylinder contains a PVC piston and piston rod with a fixed orifice in the piston head to meter the flow of gas from one end of the cylinder to the other. The top cap of the device is a hermetically sealed flat PVC disc. The piston rod passes through a hole sealed by an O-ring held in the bottom cap of the device. The load is held by a PVC arm attached to the external end of the piston rod by a string loop and passed through a plastic eye affixed to the outer cylinder wall. Thus, the load is held in position until the arm travels down to the point for snap-action release. The release time of the device is set by the initial positioning of the piston within the cylinder.

2. The existing carbon dioxide release system could be improved to give more accurate results.

II. INTRODUCTION

The Free Europe Committee, Inc. is engaged in a program of dissemination of information behind the Iron Curtain by balloon-borne leaflets. A time-release mechanism based on the loss of weight by sublimation of solid carbon dioxide is currently being used to drop the leaflet load over the proper target.

Since the present release system is inaccurate--some loads have been dropped as much as 70 miles off target--the Committee asked Arthur D. Little to study the feasibility of and to design a device that would meet the following requirements:

1. A timing accuracy of ± 5 per cent in a range of 1 to 18 hours.
2. Satisfactory operation at temperatures to -60°F.
3. Satisfactory operation at altitudes to 25,000 feet.
4. Manufacture and assembly costs of not more than $1.00 per unit.

When the Arthur D. Little program was under way, the Committee advised us of two further requirements:

5. The device should contain no metallic parts.
6. The device must release its load if it fails at any time to function properly.

These added requirements disqualified some of the devices under study.

III. SELECTION OF DEVICES FOR STUDY

At the first meeting between Arthur D. Little staff and the Free Europe Committee officials, it was agreed that ADL should select a variety of release mechanisms based on different principles. These would be studied with an eye to engineering feasibility, proper functioning under required conditions, and cost.

The timing mechanisms selected for basic study were:

1. Gaseous or liquid leakage
2. Chemical or electrochemical corrosion
3. Clockwork
4. Torsion creep
5. Radio-signal release
6. Ballast-weight loss

Initial evaluation of these possibilities led us to reject mechanisms 4, 5, and 6 and to conduct a more intensive study of the remaining three.

Further study indicated that the gaseous leakage mechanism most closely met all of the Committee's specifications, and design and development work on that system was continued.

The design, description, and evaluation of all six systems are discussed in Sections IV - IX.

IV. LEAKAGE MECHANISM

This mechanism is based on the leakage of a gas through a fixed orifice. Theoretical calculations are given in the Appendix.

Our first prototype of such a device (shown in Figure 1) was a metal cylinder capped at both ends. Inside the cylinder was a piston and rod with the rod extending through one capped end of the cylinder. In the opposite cap was a needle valve that could be set for various leakage rates. A helical steel spring in the cylinder supplied the driving force for the piston, and as an alternative, we tested a pressurized gas reservoir.

The spring-driven mechanism gave remarkably linear results of time versus piston travel; the gas-pressured system gave results that were not as linear. Nevertheless, both systems were believed acceptable.

We constructed several spring-driven mechanisms and found them to perform reproducibly both on a single-sample basis and on a sample-to-sample basis. We then reduced the weight and size by substituting some plastic parts for metal. The final prototype was constructed of PVC with a metal piston, needle valve, and spring (these we kept metallic for sake of accuracy and reproducibility).

When we were informed of the nonmetallic requirement, we redesigned the device as follows:

A fixed orifice in the piston replaced the needle valve. The flow of gas was metered by several layers of filter paper placed in the orifice and held by a retaining ring.

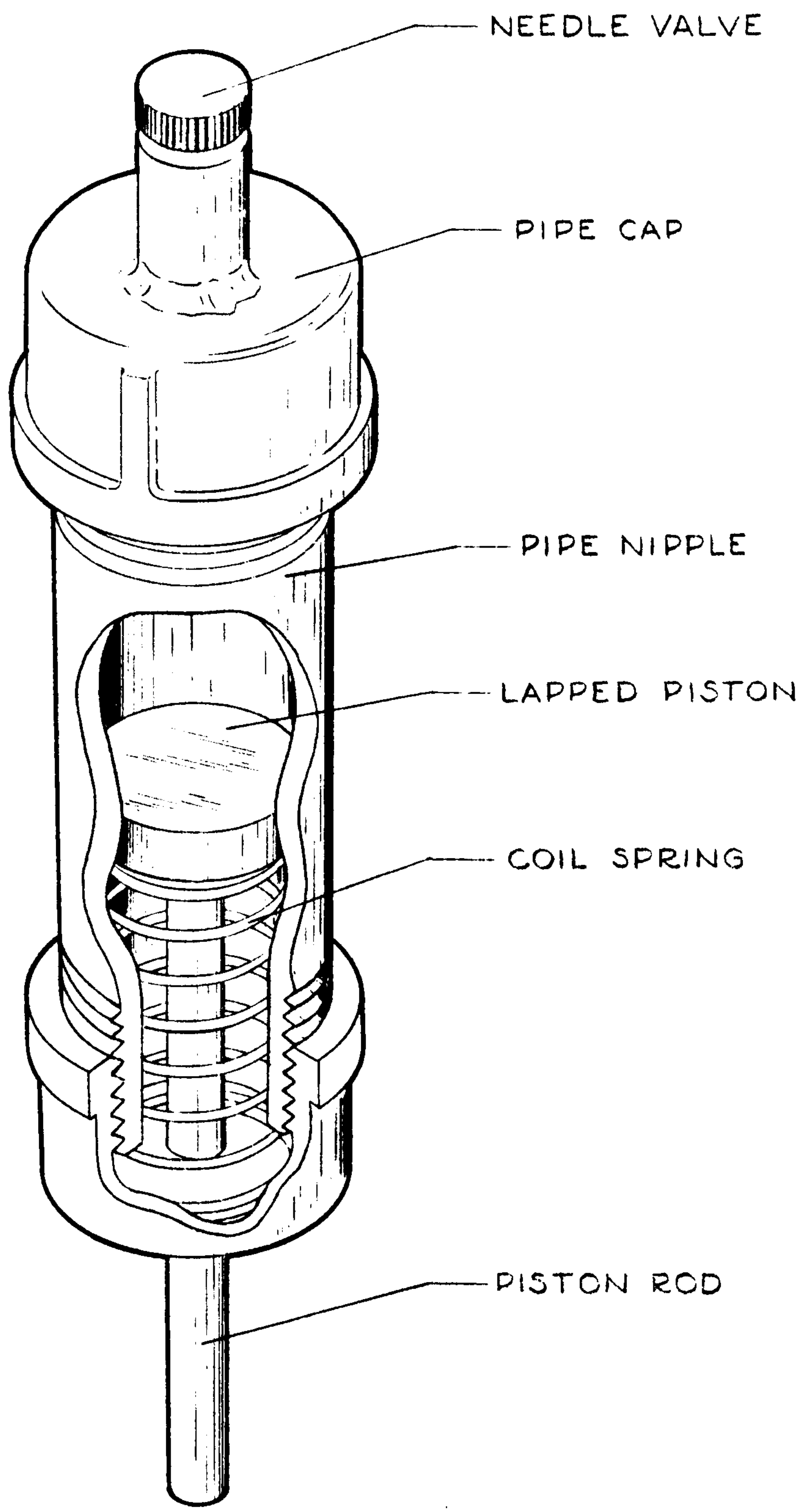
A plastic piston was built and sealed in the cylinder with an O-ring. A plastic piston rod was sealed through the bottom cylinder cap with a second O-ring. All moving parts were lubricated with powdered graphite.

The steel spring was eliminated, and the driving force was supplied by the 4-pound payload.

The payload was suspended in a "U" formed by the piston rod and a plastic retaining arm attached on one end to the piston rod with a string loop with its other end passed through a plastic eye affixed to the outer cylinder wall.

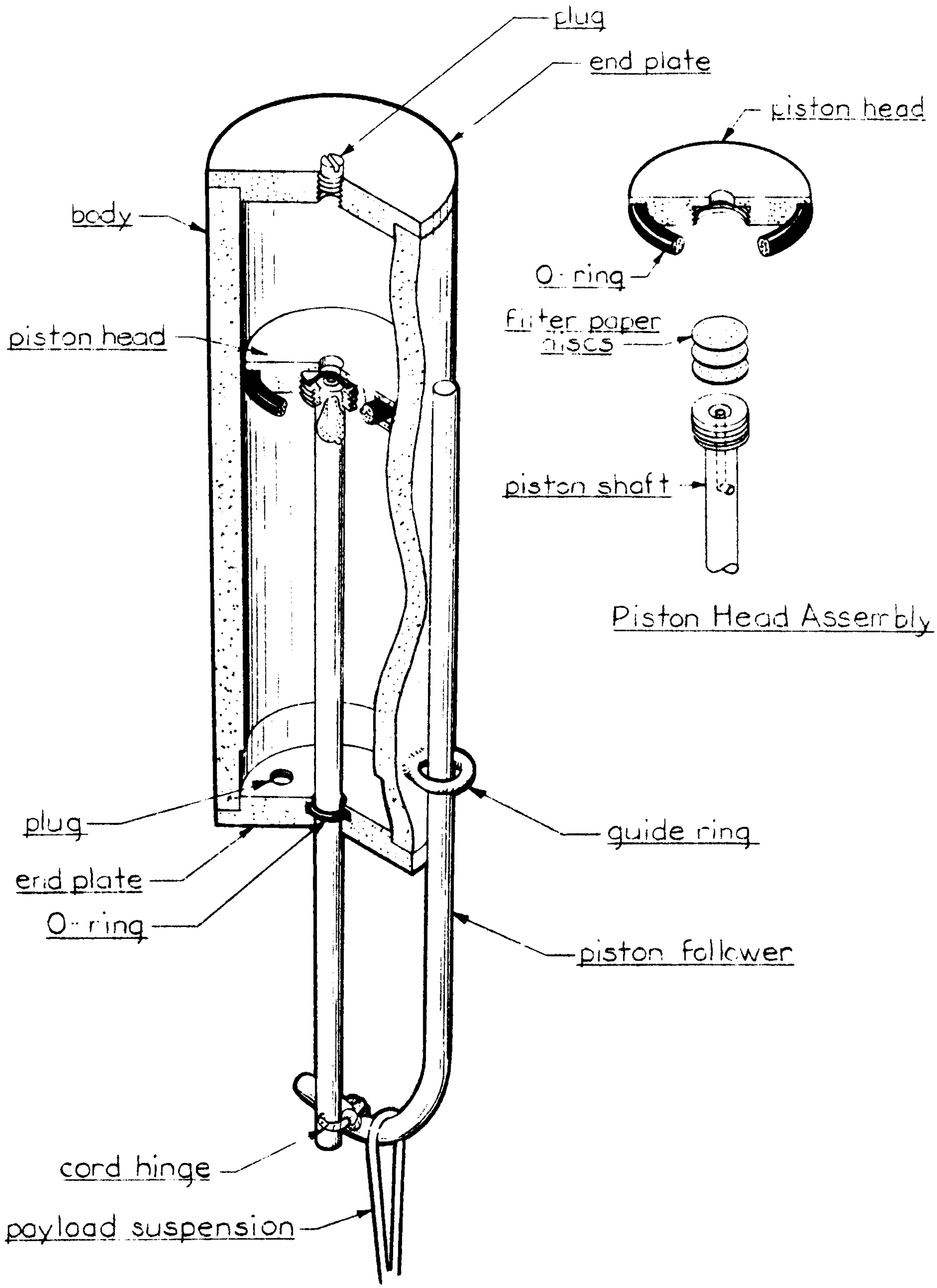
As the piston and rod traveled down the cylinder, the retaining arm slid through the eye until it fell free and released the load of leaflets.

The final design of this device is shown in Figures 2 and 2A. Several such units were built and tested for uniformity of performance at ambient conditions. The results of these tests are shown in Figures 3 and 4. These graphs show that the time-versus-travel function is quite linear and uniform both within each unit and between unit and unit. On a hand-made basis, each unit must be individually calibrated. In production, however, it should be possible to make parts uniform enough so that individual calibration would not be necessary.



PROTOTYPE DESIGN

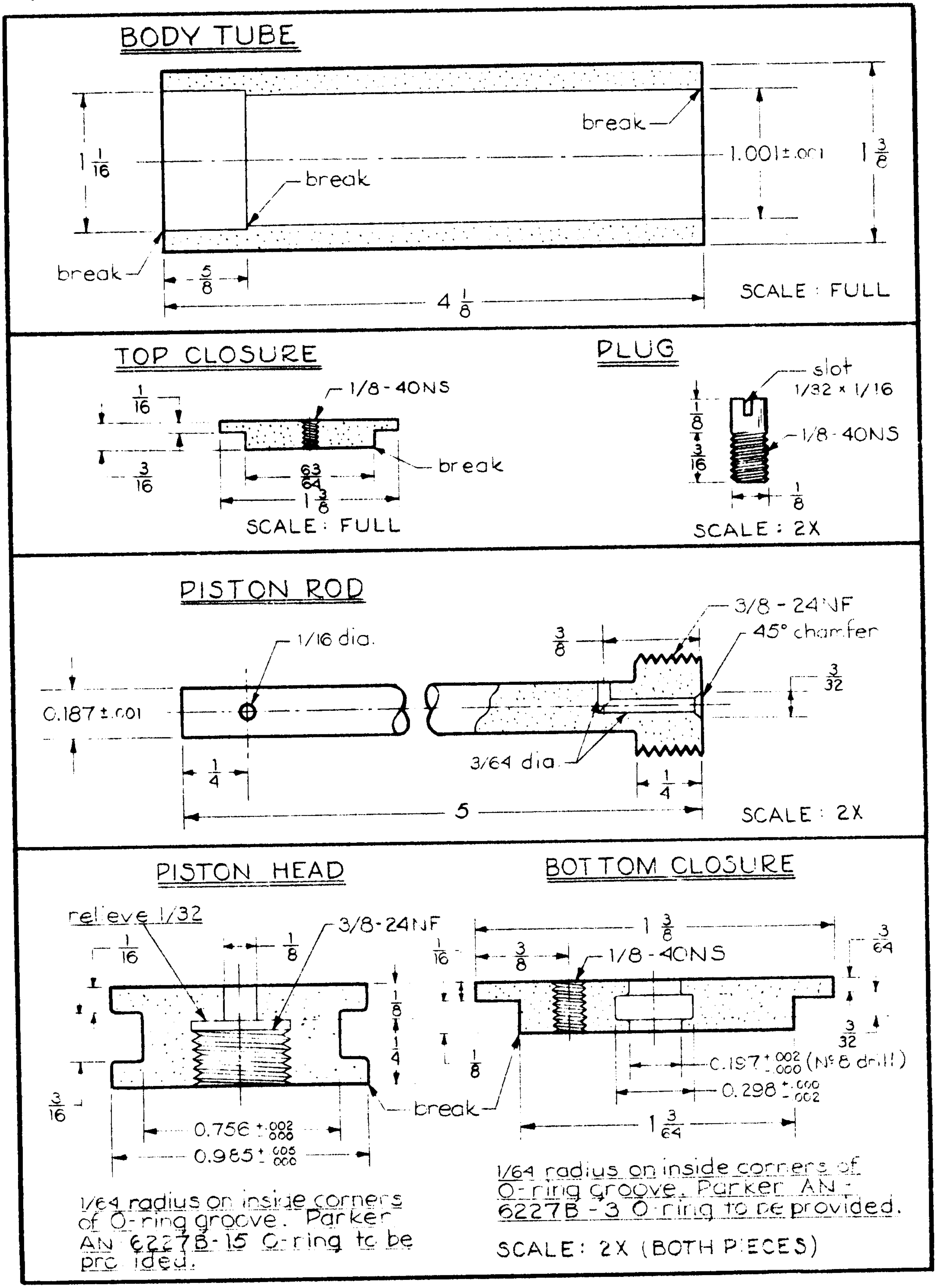
Figure 1



MODEL III TIMER

GENERAL ARRANGEMENT

Figure 2



TYPICAL PARTS DETAIL - MODEL III TIMER

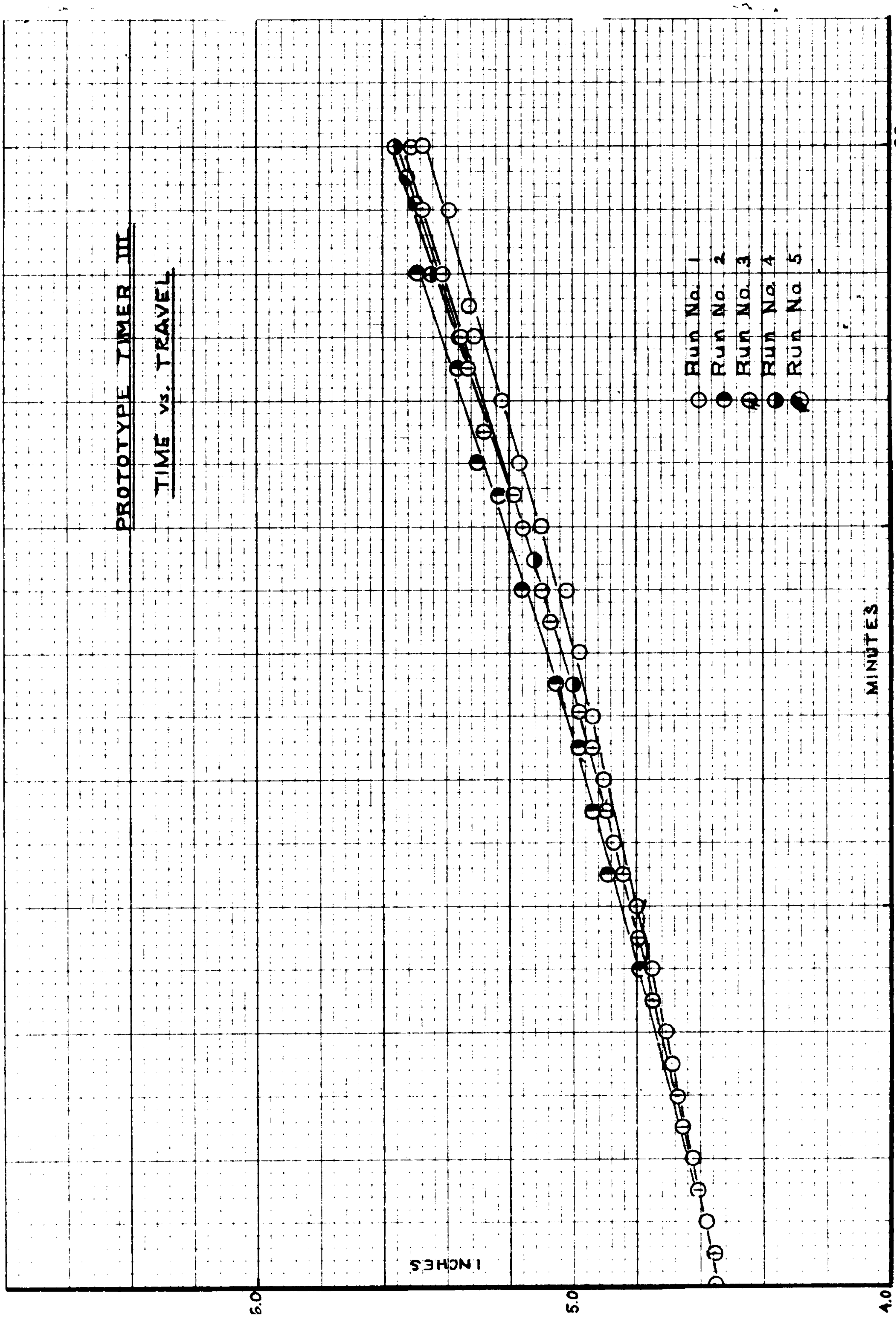

PROTOTYPE TIMER III
TIME vs. TRAVEL
Run No 1
Run No 2
Run No 3
Run No 4
Run No 5
MINUTES
INCHES
0
60
120
180
4.0
5.0
6.0

Figure 3

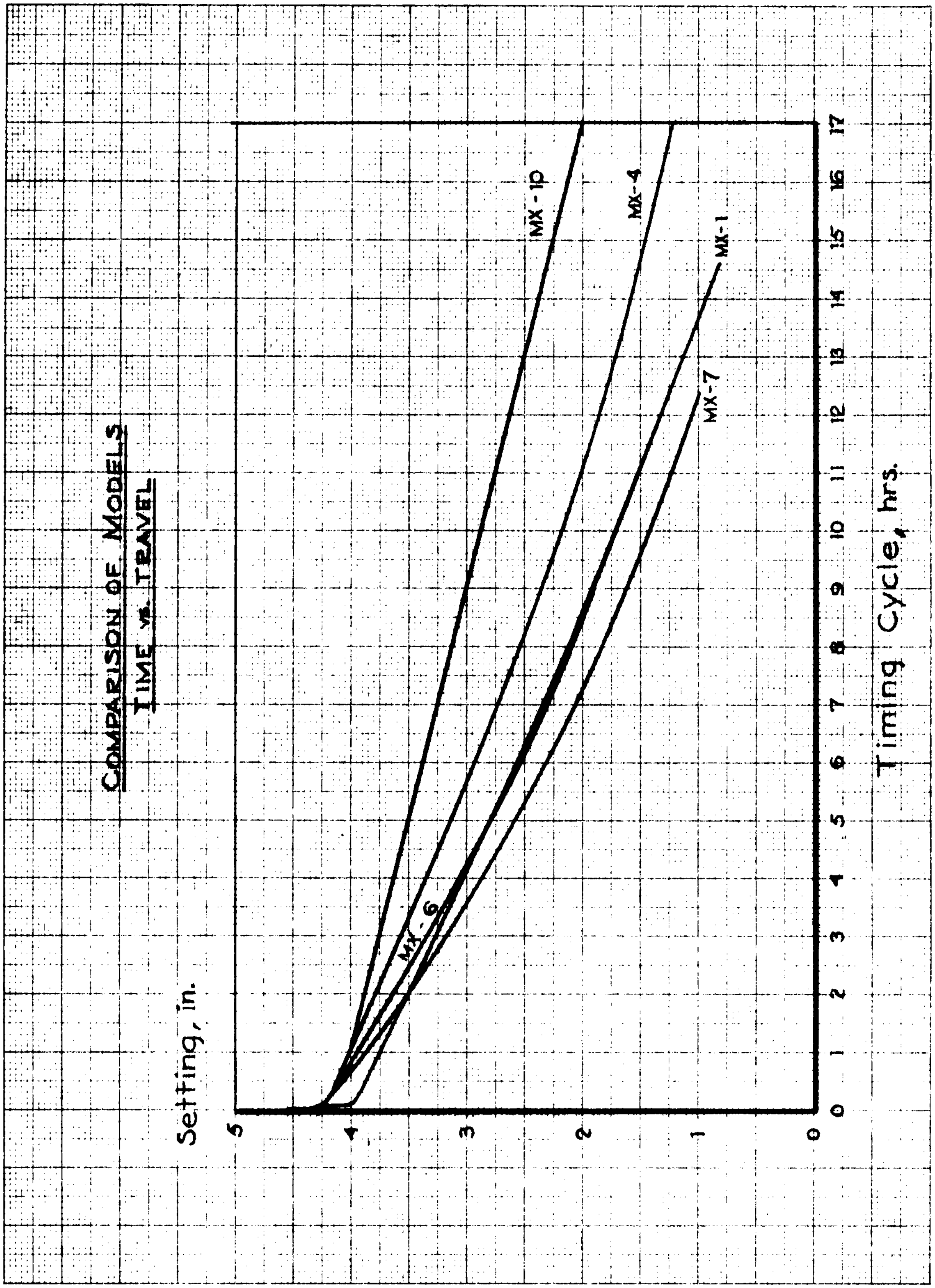

COMPARISON OF MODELS
TIME vs. TRAVEL
Setting, in.
Timing Cycle, hrs.
MX-10
MX-4
MX-1
MX-7
MX-6
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17

Figure 4

These devices were sent to the Committee for field testing. Two were test-flown in the United States. They released considerably before preset time and were returned to us for examination.* The units sent to Europe were tested at 25,000 feet with similar premature release. In addition, it was reported that an obvious bulge appeared in the cylinder walls which allowed the piston to fall freely.

Since the manufacturer's literature indicated that the plastic should be dimensionally stable under the imposed conditions, we conducted several tests of the material. We built several polyvinyl chloride tubes of the same dimensions as the cylinders, capped one end, and subjected them to an internal pressure of 14 pounds per square inch. We checked the dimensions periodically for 2.5 hours. The results of these tests are given in Table I. Little or no change occurred in the tube dimensions.

(It is possible that the bulging noted in the European tests could have come from plasticizer material in the entrapped air. In view of this possibility, we believe that the parts should be joined by heat-sealing instead of by organic adhesives. Extreme care must be used in heat-sealing, however, since heat distortion can result.)

Further examination of the units tested in Europe showed that gas had leaked between the piston rod and O-ring seal. This leakage was corrected by a decrease in the diameter of the hole in the bottom cylinder cap. Two new devices with the above modification were built and tested both in vacuum and under water. We found them to be hermetically sealed.

In low-temperature tests, the units performed satisfactorily at -20°F but they failed at -40°F. This failure was blamed on the accumulated thermal shrinkage at this lower temperature.

(A discussion of this problem with the Committee resulted in a decision that material, not mechanical design, should be modified.)

We understand that these two units are now being tested at reduced altitudes by the Committee.

PRODUCTION

Should the Committee consider future mass production of the plastic devices, the following recommendations should be considered:

1. The device should not be put into initial large scale production. Pilot construction of about 1,000 units should be undertaken with tentative production techniques and tooling. For cylinder construction, such techniques

* RAVEN RAN THESE TESTS — RELEASE OCCURRED AT ABOUT ½ HOUR ALTHOUGH SETTING WAS FOR 10 HOURS.

TABLE I

DIMENSIONAL STABILITY TEST OF CYLINDERS

Position*	Zero Reading Atmos. P.	Reading at 15 lbs. Internal Pressure: 13 hr 10 min	13 hr 45 min	14 hr 15 min	14 hr 45 min	15 hr 15 min	15 hr 45 min
Unit #1							
1a	1.3325"			1.3325"	1.330"	1.330"	1.331"
1b	1.3255"			1.3255"	1.3255"	1.326"	1.3255"
2a	1.3315"	1.3315"	1.3305"	1.3315"	1.330"	1.331"	1.331"
2b	1.3255"	1.325"	1.326"	1.325"	1.3255"	1.325"	1.3255"
3a	1.3315"			1.3325"	1.331"	1.330"	1.3315"
3b	1.3275"			1.3275"	1.326"	1.327"	1.326"
Unit #2							
1a	1.3295"			1.330"	1.3305"	1.331"	1.330"
1b	1.3285"			1.328"	1.3275"	1.3275"	1.3275"
2a	1.3316"	1.333"	1.331"	1.3315"	1.3315"	1.3305"	1.3305"
2b	1.3287"	1.3285"	1.327"	1.327"	1.327"	1.3275"	1.327"
3a	1.3315"			1.331"	1.330"	1.331"	1.3315"
3b	1.3285"			1.3285"	1.328"	1.3275"	1.3275"
Unit #3							
1a	1.327"			1.3275"	1.327"	1.3275"	1.327"
1b	1.3285"			1.328"	1.3275"	1.328"	1.3275"
2a	1.3285"	1.3285"	1.327"	1.328"	1.3275"	1.3275"	1.3270"
2b	1.3285"	1.328"	1.3275"	1.3285"	1.326"	1.327"	1.326"
3a	1.328"			1.3275"	1.327"	1.327"	1.327"
3b	1.328"			1.3285"	1.328"	1.3275"	1.327"

* Position 1a, 2a, 3a indicate equal spacing down cylinder in straight line.
Position 1b, 2b, 3b same only rotated 90°.

TABLE I (Cont.)

DIMENSIONAL STABILITY TEST OF CYLINDERS

Unit #4

Posi-	Zero Reading	---------- Reading at 15 lbs. Internal Pressure ----------					
tion*	Atmos. P.	13 hr 10 min	13 hr 45 min	14 hr 15 min	14 hr 45 min	15 hr 15 min	15 hr 45 min
1a	1.330"			1.331"	1.331"	1.331"	1.331"
1b	1.3265"			1.3275"	1.326"	1.326"	1.326"
2a	1.330"	1.333"	1.332"	1.331"	1.3315"	1.3315"	1.332"
2b	1.3275"	1.327"	1.328"	1.328"	1.327"	1.327"	1.3265"
3a	1.3315"			1.3315"	1.331"	1.3315"	1.332"
3b	1.3265			1.3265"	1.3265"	1.326"	1.326"

* Position 1a, 2a, 3a indicate equal spacing down cylinder in straight line.
Position 1b, 2b, 3b same only rotated 90°.

would probably require precision casting around a polished core. The other parts probably could be stamped or heat-formed. The orifice should be moved from the center to one side of the piston. All units produced in the pilot lot should be tested under actual operating conditions so that an inspection procedure could be devised that would do away with the necessity for calibrating each device in production. If the results of the pilot lot indicate that mass production is feasible, the Committee should proceed with a limited production with further control testing.

2. The devices should be studied after storage under various conditions so that any distortion may be noted. Cold flow due to forming stresses in the plastic could change the dimensions. Such a condition could be eliminated by proper selection of materials and exact production conditions.

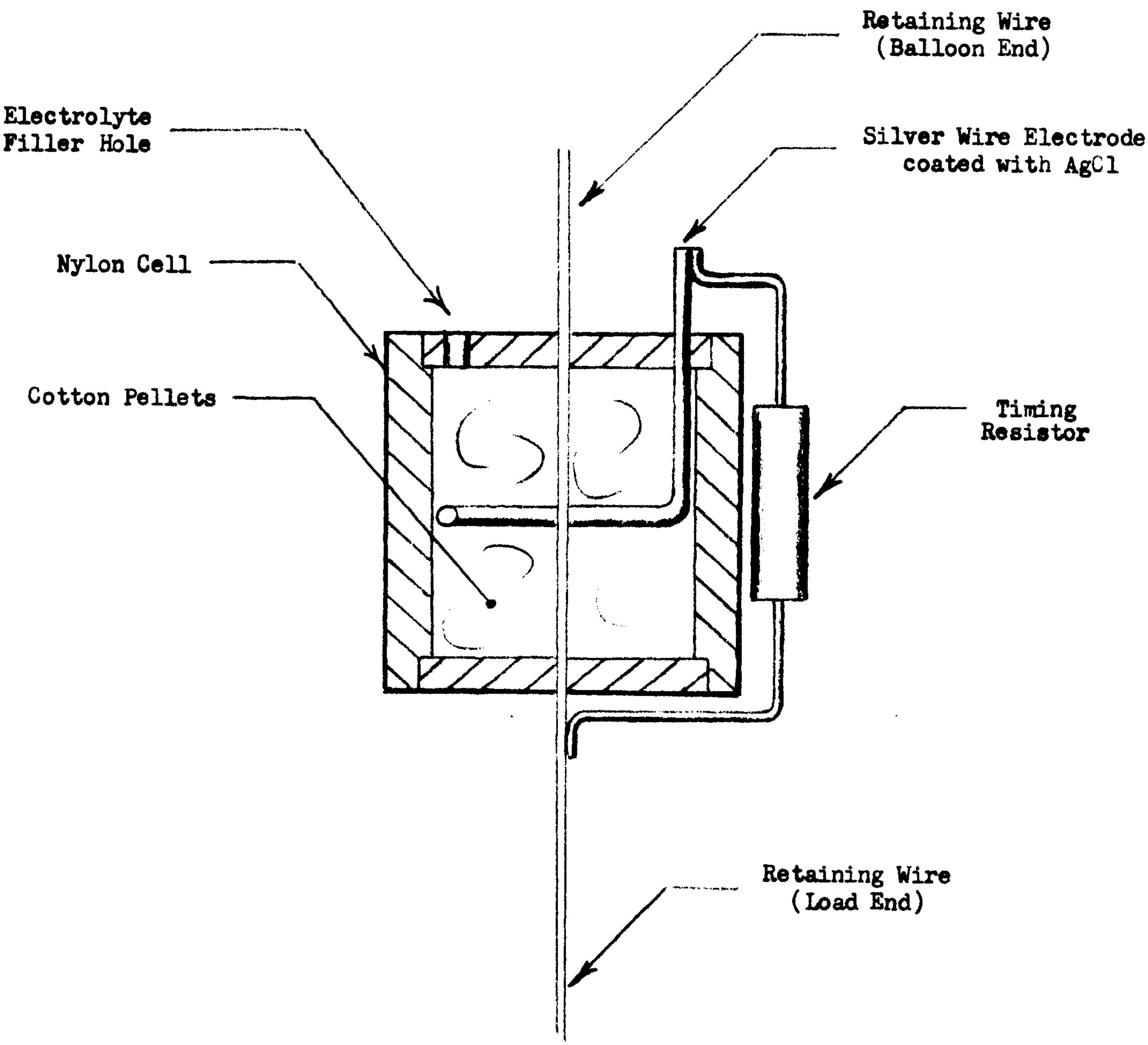
3. The Committee should consider the use of unskilled labor to assemble and test the device. A minimum amount of training would be required.

V. ELECTROCHEMICAL OR CHEMICAL CORROSION

This system involves the use of either an electrolytic or a chemical cell. In our study emphasis was placed on the former, since it was known that such a system is less temperature-dependent than is chemical corrosion. A preliminary design is shown in Figure 5.

The mechanism of such a cell involved the simultaneous plating out of silver onto a silver anode and electrolytic corrosion of a metallic retaining wire. Variations in time could be obtained by a change in the external resistance of the cell.

This device met the requirements of cost and size but failed in other respects. Under the best of conditions, we estimated a time tolerance of not less than $\pm$ 10 per cent, and with the specified operating temperature of -60°F, it was doubtful if even this tolerance would be realized. In addition, since the concentration of the electrolyte would have to be high so that it would not freeze at the low temperatures encountered, the tolerance spread would be further affected. Finally, failure of such a device would most likely be caused by an open circuit. Thus the mechanism would not release within a reasonable time. We decided, therefore, that this system would not be studied further. The chemical corrosion mechanism was known to have even more marked limitations and was also discarded.

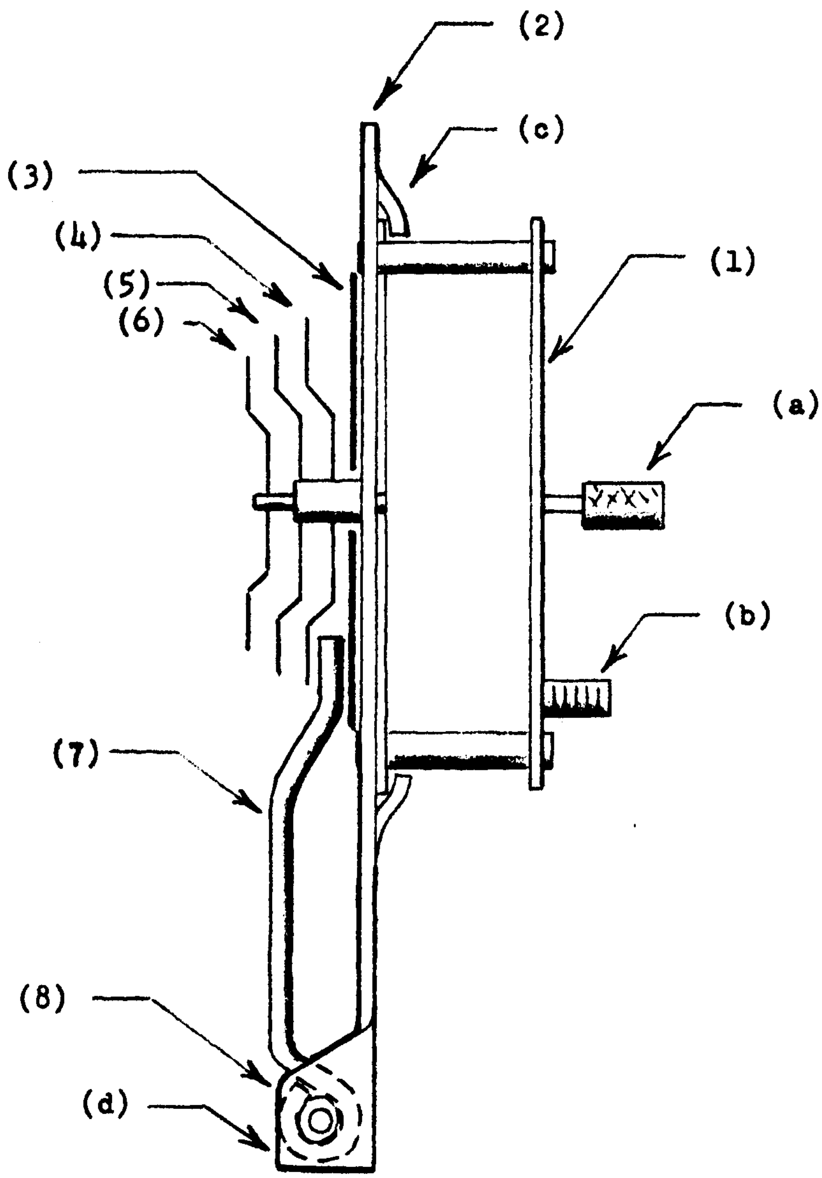


ELECTROLYTIC CORROSION CELL

Figure 5

VI. CLOCKWORK RELEASE MECHANISM

The most reliable timing mechanism would be based on a mechanical clockwork-type device. We realized that such a device would undoubtedly not meet the low cost requirement, but it was investigated because of its extreme reliability. A proposed design is shown in Figure 6. After conferring with clockwork manufacturers and fabricators, we estimated that such a mechanism could not be produced for less than $1.70, with a more realistic estimate of $2.00 or $2.50 per unit. In addition, we could conceive of no obvious mechanism that would fail in the released position. Therefore, this approach was not pursued. When we learned that no metallic parts could be employed, it was our feeling that although it would be possible to construct a clockwork device of nonmetallic parts, the cost would not be significantly reduced. Furthermore, the mechanism would be considerably less accurate than a metallic clockwork.



Parts Identification

(1) Clockwork (Westclox Model 66)
(2) Mounting Frame (Sheet Aluminum)
(3) Time-Scale Decal
(4) #1 Hour Disc (Stamped Aluminum)
(5) #2 Hour Disc (Stamped Aluminum)
(6) Minute Disc (Stamped Aluminum)
(7) Trip Lever (Bent Wire)
(8) Rivet or Eyelet

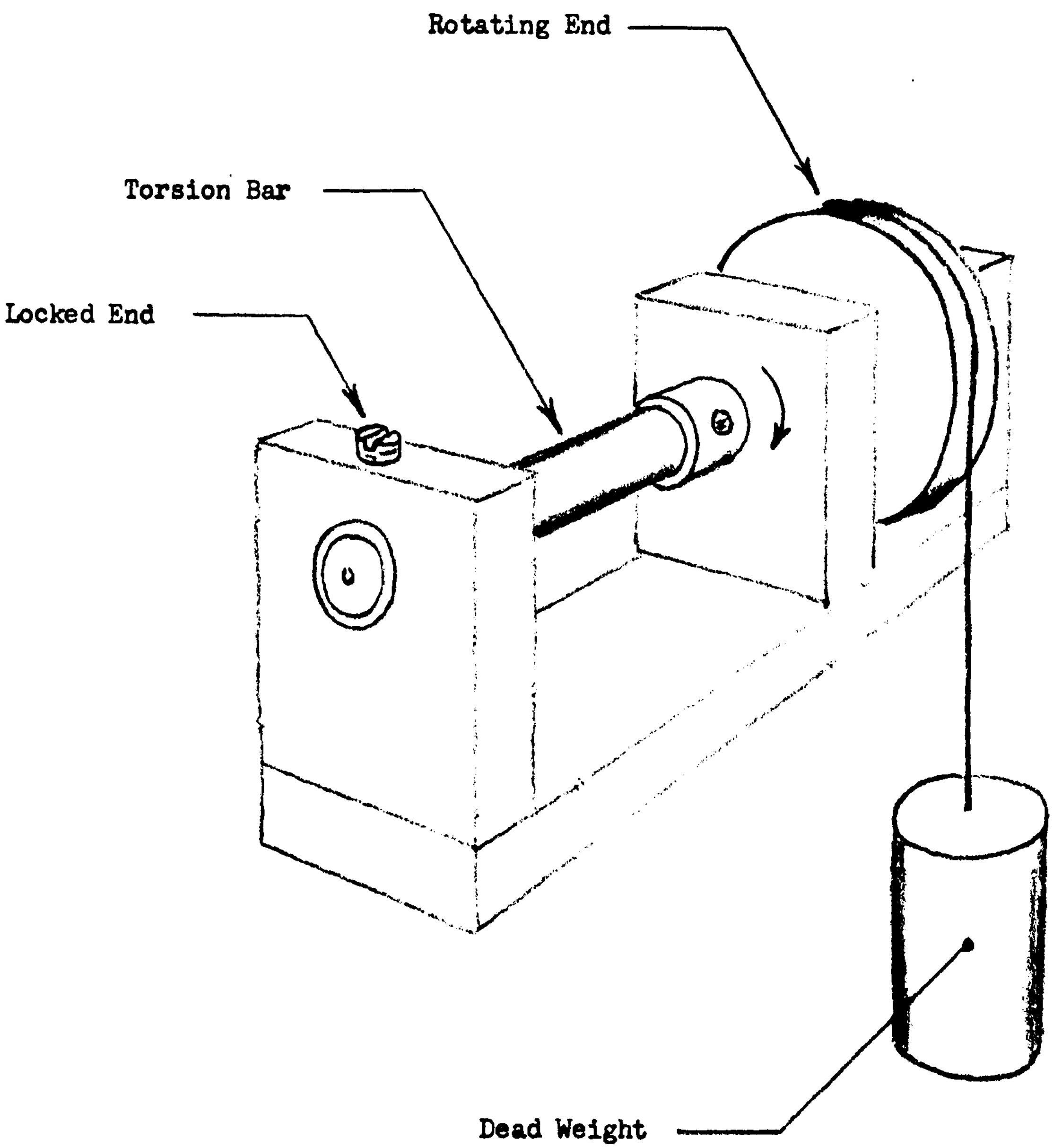
(a) Setting Knob
(b) Winding Stem
(c) Holding Down Lug
(d) Bent Ears

CLOCKWORK RELEASE DEVICE

Figure 6

VII. TORSION DEVICE

This device involved the failure of a soft metallic bar when an axial force was applied. Such a system might have the design as shown in Figure 7. We designed a test jig to investigate the reliability of such a system. Initial results with a 50/50 tin-lead-solder mixture showed that the rate of creep was remarkably linear. We decided, however, that the investigation of such a mechanism should be put aside in favor of other mechanisms, since such a development would involve a lengthy study of soft metallic alloys. In addition, even if a device could be developed along these lines, a severe quality-control program would be encountered in production, since nondestructive testing and calibrating of such a device would be quite difficult.



TORSION TEST JIG

Figure 7

VIII. RADIOTRIP MECHANISM

A radiotrip device could be designed which, on receipt of a fixed control signal, would activate a release mechanism. However, such a mechanism would require an internal power supply that would be costly and heavy and would offer a supply difficulty. In addition, the success of such a mechanism would require a knowledge of the exact location of the balloons and a different signal for each balloon or group of balloons.

IX. BALLASTED RELEASE MECHANISM

The release mechanism originally employed by the Free Europe Committee involved a ballasted release mechanism activated by the loss of weight of dry ice by sublimation. Other such mechanisms utilizing the leakage of solid or liquid materials could be visualized. Considerable thought was given to a liquid-leakage mechanism, since there are known liquids that have little viscosity temperature change. However, for operating times up to 18 hours, the amount of liquid required would weigh too much.

We believe that the original carbon dioxide system could be improved to the point where its time tolerance would be acceptable. The first approach to such a redesign would be to cast the solid carbon dioxide in a cylinder for a more stable sublimation rate. This would be consistent with the practice employed by the manufacturer of propellants for control of burning rates. Other improvements would include the substitution of pinpoint fulcrums for the original looped hinges in the wire release mechanism. It was felt that by such minor changes, the original low-priced mechanism would then be made acceptable. It is our understanding that other considerations have caused this approach to be eliminated.

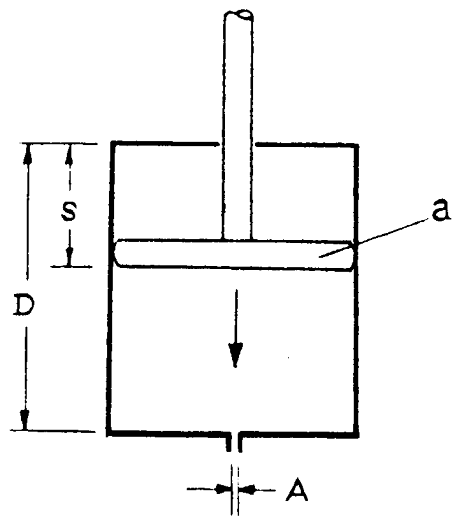
APPENDIX

APPENDIX

Time as a Function of Distance of Travel

DERIVATION

With reference to the diagram, we establish the following relations:



Volume at any time t

$$V = a(D-s) + V_o \qquad (1)$$

where

V = Volume at any time t
a = area of piston
s = distance between position of piston at time t and its position at rest, i.e., when flow through orifice has ceased
D = Distance between initial setting ($t = o$) and at rest position
V_o = Volume of gas retained in cylinder at rest position

Force on piston at any time t

Force of atmosphere + Force of spring = Force exerted by gas + Force of friction

$$ap_a + k(D-d) = ap + F \qquad (2)$$

where

p_a = atmospheric pressure

k = spring constant

p = pressure of contained gas

F = force of friction

Relation between Pressure, Volume, and Mass of Contained Gas

$$PV = \frac{m}{M} RT \tag{3}$$

where m = mass of contained gas
M = Molecular weight of gas

Flow Through Critical Orifice

For a critical orifice the mass rate of flow is directly proportional to the upstream pressure, i.e.

$$\frac{dm}{dt} = -cp \tag{4}$$

where c is a constant for the particular gas and orifice (also involves orifice area and temperature of gas).

A relation between elapsed time and piston position was derived from the above equations in the following manner:

From (3) by differentiation

$$p\frac{dv}{dt} + V\frac{dp}{dt} = \frac{RT}{M} \frac{dm}{dt} \tag{5}$$

substituting (4) in (5) and re-arranging

$$V \frac{dp}{dt} = -\frac{RT}{M} cp - p \frac{dv}{dt} \tag{6}$$

Differentiation of (2) yields

$$-k \frac{ds}{dt} = a \frac{dp}{dt}$$

or

$$\frac{dp}{dt} = -\frac{k}{a} \frac{ds}{dt} \tag{7}$$

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also from (2)

$$p = \frac{k(D-s) + ap_a - F}{a} \tag{8}$$

Differentiation of (1) yields

$$dV = - ads \tag{9}$$

Substituting (1) (7) (8) and (9) in (6)

$$\left[a(D-s) + V_o\right]\left[k/a \frac{ds}{dt}\right] = \left[k(D-s) + ap_a - F\right]\left[\frac{RTC}{Ma} - \frac{ds}{dt}\right]$$

or

$$\frac{k}{a}\frac{ds}{dt}\left[a(D-s) + V_o\right] + \frac{ds}{dt}\left[k(D-s) + ap_a - F\right] = \left[k(D-s) + ap_a - F\right]\frac{RTC}{Ma}$$

separating variables

$$\frac{k(D-s)\,ds + \frac{kV_o}{a}\,ds}{k(D-d) + ap_a - F} + ds = \frac{RTC}{Ma}\,dt$$

For ease of integration let $Q = k(D-s)$ $dQ = - kds$ $ds = -dQ/k$

$$\frac{\frac{-dQ}{k} - kV_o/a\,\frac{dQ}{k}}{Q + ap_a - F} - \frac{dQ}{k} = \frac{RCT}{aM}\,dt$$

Integration yields

$$\frac{1}{k}\left[\cancel{F}-ap_a - Q - (F-ap_a)\ln(F-ap_a-Q) - \cancel{F} + ap_a + Q_o + (F-ap_a)\ln(F-ap_a-Q_o)\right]$$

$$+\frac{V_o}{a}\left[\frac{1}{-1}\ln(F-ap_a-Q) + \ln(F-ap_a-Q_o)\right] - \frac{Q}{k} + \frac{Q_o}{k} = \frac{RCT}{aM}\,t$$

$$\frac{2}{k}(Q_o-Q) + \frac{(F-ap_a)}{k}\ln\frac{(F-ap_a-Q_o)}{(F-ap_a-Q)} + \frac{V_o}{a}\ln\frac{(F-ap_a-Q_o)}{(F-ap_a-Q)} = \frac{RCT}{aM}\,t$$

$$\frac{RCT}{aM}\ t = 2s + \left[\frac{(F-ap_a)}{k} + \frac{V_o}{a}\right] \ln \frac{(F-ap_a - kD)}{F-ap_a-k(D-s)}$$

$$= 2s + \left[\frac{F-ap_a}{k} + \frac{V_o}{a}\right] \ln \frac{1}{1 + \dfrac{s}{\dfrac{F-ap_a}{k} - D}}$$

Units

C as used above $= \dfrac{0.533\ Ac'}{\sqrt{T}}$

where

0.533 = constant for air and nitrogen

T = Absolute temperature in °R (°R = °F + 460)

A = Area of orifice in in^2

c' = 1 (approx.), has units of ($\sqrt{°R}$/sec

R = 18,540 $\left(\dfrac{\text{lb-in}}{°R}\right)$

T = °R (°R = °F + 460)

a = in^2

M = lb

then s will be in inches

Expressing t in hours we obtain

$$t = 2.81 \times 10^{-8} \frac{aM}{A\sqrt{T}} \left\{2s + \left[\frac{F-ap_a}{k} + \frac{V_o}{a}\right] \ln \frac{1}{1 + \dfrac{s}{\dfrac{F-ap}{k} - D}}\right\}$$

For nitrogen M = 28.0 At 70°F T = 530

then

$$t = 3.43\text{x}10^{-8}\ \frac{a}{A} \left\{2s + \left[\frac{F-ap_a}{k} + \frac{V_o}{a}\right] \ln \frac{1}{1 + \dfrac{s}{\dfrac{F-ap_a}{k} - D}}\right\}$$

Application

Preliminary calculations indicated that the volume of a cylinder would have to be very large in order to achieve an elapsed time of 15 hours with an orifice of any reasonable size, i.e. 10^{-6} in^2, the latter being taken as a lower limit. An example follows:

Assumptions

Dimensions of cylinder - I.D. = 2 in.
D. = 4 in

Spring constant k = 25 lb/in (This would result in a maximum abs. pressure of 100 lb/in^2)

p_a = 14.7 lb/in^2

F = 5 lb

t = 15 hrs

a = 3.14 in^2

s = D = 4 in

V_o = 0

Then

$$A = \frac{3.43\times10^{-8}\times3.14}{15}\left\{8 + \left[\frac{5-46.1}{25}\right] \ln \frac{1}{1+\dfrac{4}{\dfrac{5-46.1}{25}-4}}\right\}$$

$$= 7.18\times10^{-9} \left\{8 + 1.643 \ln 0.345\right\}$$

$$= 7.00 \times 10^{-8}$$

Thus the annular space of the orifice (assuming it consists of a needle valve) can only be 7×10^{-8} in^2.

The area for the annular space is given by

$$A = \frac{\pi}{4}(D_1^2 - D_2^2)$$

where

D_1 = diameter of orifice

D_2 = diameter of needle

Given D_1 and A

$$D_2 = \sqrt{D_1^2 - \frac{4}{\pi} A}$$

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Using 12.5×10^{-3} in. as an orifice diameter (smallest drill readily used and available)

$$D_2 = \sqrt{156.25 \times 10^{-6} - 8.92 \times 10^{-8}}$$
$$= \sqrt{1.546 \times 10^{-4}}$$
$$= 12.4996 \times 10^{-3} \text{ inches}$$

That is, the diameter of the needle would have to be 4 ten millionths of an inch smaller than the diameter of the orifice to achieve a fifteen-hour time interval.

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